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MINORU AWADA and CHARLES R. LONG

HAWAII AGRICULTURAL EXPERIMENT STATION, UNIVERSITY OF HAWAII

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THE AUTHORS

Minoru Awada is Associate Plant Physiologist, Hawaii Agricultural Experiment Station, College of Tropical Agriculture, University of Hawaii.

Charles R. Long is Research Associate, Hawaii Agricultural Experiment Station, College of Tropical Agriculture, University of Hawaii, Hilo.

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INTRODUCTION

Papaya plants grown on a'a lava soil in the Puna area, on the Island of Hawaii, have responded tremendously to phosphorus (P) fertilization (*1, 16*). To obtain a rational basis for fertilizing papaya plants with P in Hawaii, a study (*1*) was initiated in Puna to determine the critical P level in a selected plant tissue. As a result of that study, a "recently matured" petiole was selected as the P index tissue, and a tentative P critical level for maximum yield of papaya was determined.

Because the sale of papaya fruits is presently regulated under the provisions of the Federal marketing order, the fruits must satisfy certain grading standards before being marketed as fresh fruits. Hence, a P fertilizer treatment should be evaluated with marketable fruits produced by trees under that treatment rather than with yield of all fruits. The proportion of the various fruit sizes produced by trees in a treatment plot should also be considered because a high proportion of smaller-sized fruits produced by trees in that plot will lower the relative merit of the treatment even though the yield of marketable fruits is increased. In addition, the total soluble solids content of fruits produced should be considered. Thus, a critical petiole-P level determined after considering all these factors is more useful to the grower than one based solely upon total fruit yield.

Another aspect of P fertilization in papaya that needs to be studied is the timing of fertilization in the developmental stage of the plants in order to obtain maximum growth and fruit yield responses. Jones and Warren (*10*) reported a greater yield of tomatoes when a P "starter" solution was used at planting time than when P was applied to established plants. Brenchley (*6*) reported that when P was applied early in the developmental stage of barley plants, growth was better than when P was applied either intermittently or late. In papaya, P fertilizer applied to plants *before* the bearing stage may be more beneficial than that applied throughout the bearing stage, as practiced by most growers in Hawaii.

This study was made (1) to establish the critical level of P in petioles of papaya, and (2) to determine the most opportune time for P fertilization in the developmental stage of the plant to obtain optimal fruit yield.

MATERIALS AND METHODS

This study was conducted at the Malama-Ki Experimental Station (elevation about 360 feet), Hawaii Agricultural Experiment Station, Puna, Island of Hawaii. The soil is a relatively unweathered, rocky material mixed with a high proportion of organic residues, and it has both low cation-exchange and low buffering capacities. This soil was formerly classified as a Lithosol in the great soil group, but in the

Table 1. Mean monthly air temperature and monthly rainfall records, Malama-Ki, Puna, Hawaii, during study

Year and month	Temperature (°F) Maximum	Temperature (°F) Minimum	Rain (inches)	Year and month	Temperature (°F) Maximum	Temperature (°F) Minimum	Rain (inches)
1970				*1971*			
June	80.9	68.0	5.6	July	81.2	67.1	4.8
July	81.6	68.3	12.6	Aug.	82.0	66.1	2.6
Aug.	81.7	69.1	14.6	Sept.	81.6	66.9	6.9
Sept.	82.5	67.9	5.9	Oct.	80.6	66.4	4.4
Oct.	81.5	68.2	8.0	Nov.	77.6	65.2	12.2
Nov.	78.9	67.1	14.2	Dec.	75.2	63.7	17.8
Dec.	76.4	65.5	27.2				
				1972			
1971				Jan.	74.9	62.7	16.4
Jan.	75.8	64.3	32.4	Feb.	76.0	63.4	10.5
Feb.	78.2	63.1	5.9	March	79.5	64.6	2.6
March	76.4	63.5	10.8	April	76.7	65.4	9.9
April	76.9	65.5	29.5	May	79.2	65.6	6.9
May	78.7	64.2	5.1	June	80.2	66.9	6.0
June	79.6	65.9	3.9	July	81.0	68.5	6.3

Table 2. Phosphorus fertilizer treatments

		From vegetative to flowering stages		From flowering through fruiting stages		Total P applied (lb.)	
Treatment	Time of application	Lb. P/tree/2.5 weeks	No. of applications	Lb. P/tree/6 weeks	No. of applications	Per tree	Per acre
1	Early	0	0	0	0	0	0
2	Early	0.0294	6	0	0	0.1764	96
3	Early	0.0613	6	0	0	0.3678	200
4	Early	0.1532	6	0	0	0.9192	500
5	Early	0.3067	6	0	0	1.8402	1001
6	Late	0.0294	6	0.0159	12	0.3672	200
7	Late	0.0294	6	0.0619	12	0.9192	500
8	Late	0.0294	6	0.1386	12	1.8396	1001

recent classification system (*13*), it is classified as a Typic Tropofolists belonging to the order Histosols.

The weather records during the study (Table 1) show that the monthly mean maximum air temperature ranged between 82.5 and 74.9° F, while the minimum ranged between 69.1 and 62.7° F. Rainfall distribution, however, was not uniform, and it is likely that at times drought affected fruit production and tree growth.

Papaya seeds, *Carica papaya* L. cv. 'Solo', were sowed in planting holes on March 3, 1970. The young plants were supplied with moderate quantities of a mixed fertilizer (10–10–10) at monthly intervals for 4 months; this provided each tree with 0.011 lb. P, for a total of 6 lb. P/acre. Plants were then thinned to one per planting hole, and treatments were initiated (Table 2).

Treatments were designated "early" (treatments 1–5) and "late" (treatments 6–8).

1. Early treatments 1–5: Differential quantities of P fertilizer were applied at about 2½-week intervals during the vegetative stage until plants flowered at the age of 6.8 months.
2. Late treatments 6–8: After application of P at the same rate as treatment 2 during the vegetative to flowering stages, differential quantities of P fertilizer were applied at 6-week intervals during the flowering through bearing stages.

At the vegetative stage, plants were supplied nitrogen (N) and potassium (K) fertilizers at monthly intervals, with increasing quantities as the plants became larger. At the flowering stage and thereafter, each tree was supplied with 0.25 lb. N and 0.42 lb. K at 6-week intervals.

Each application of N consisted of 0.125 lb. N from urea and 0.125 lb. N from ammonium sulfate; K and P were supplied as muriate of potash and as superphosphate, respectively. The fertilizers were broadcast over the soil area from about 1 foot from the tree-trunk base to the "dripline."

Eight treatments (numbered 1 through 8) were replicated six times in a randomized block design, and treatments 3 to 8 were factorially arranged. Each plot consisted of six hermaphroditic and female trees; data from three hermaphroditic trees were taken throughout the study.

Surface soil was sampled at times to determine pH. When the soil pH became about 5.0, 1 or 2 lb. finely ground coral limestone were supplied to each tree.

Mature hermaphroditic fruits were harvested at weekly intervals from February 23, 1971 to July 25, 1972. From February 23, 1971 to November 17, 1971, the harvested fruits from each plot were graded into two classes: marketable fruits of Hawaii grades No. 1 and No. 2, and culls. From November 24, 1971 to July 25, 1972, the harvested fruits were graded into three classes: grade No. 1, grade No. 2, and culls. The number of fruits in each grade was then ascertained, and each group of similar-sized fruits was weighed.

The following is a brief description of the Hawaii grading standards:

Grade No. 1. Fruits are pyriform-shaped and weigh between 14 and 32 ounces. The percentage of soluble solids in the fruits must be above 12 percent.

Grade No 2. Fruits have shapes that deviate slightly from pyriform, but they satisfy weight and soluble solids requirements of No. 1. Fruits that weigh between 9 and 14 ounces but satisfy the requirements of No. 1 also belong to this group.

Culls. Fruits are of the elongated or carpellodic types. All fruits that weigh less than 9 ounces belong to this group.

Two fruits, one from each tree in a plot, were sampled three times throughout the study to determine the concentration of soluble solids. Flesh from the longitudinal half of a fruit was homogenized in a Waring blender, and the percentage of total soluble solids was determined with a hand refractometer on 1 to 2 drops of the homogenized flesh.

The recently matured petioles were sampled six times throughout the study for determination of nutrients. Three petioles, one from each tree in a plot, were collected and combined into a sample. The petioles were weighed, washed with detergent, rinsed with distilled water, cut into pieces, and dried overnight at 70 to 75°C. The dried sample was weighed, then ground in a stainless steel mill to pass through a 20-mesh screen. Chemical determinations of the nutrients were made on the dry, ground material. The procedures for determinations of the macronutrients were described in an earlier report (*3*). In the determinations of iron (Fe), zinc (Zn), copper (Cu), and manganese (Mn), a weighed, dry sample was digested with nitric and perchloric acids, the cleared extract was made to volume, and on this solution the concentrations of these nutrients were determined with an atomic absorption spectrophotometer. In boron (B) analysis, a weighed, dry sample was ashed in a muffle furnace at 500°C for 4 hours and the ash dissolved in 10 milliliters of 0.36 *N* sulfuric acid; on this solution, the concentration of B was determined with the Technicon Autoanalyzer using the carmine red reagent.

The tree-trunk circumference 6 inches above the ground was measured initially and at regular intervals throughout the study; from these data, the growth rate of the tree-trunk circumference was calculated. The fresh weight of the petioles sampled for determination of the nutrients also served as an index of growth.

The statistical procedures described in Snedecor (*17*) were followed. In calculating the mean squares for variance analysis when the independent variable is unequally spaced, Grandage's description (*9*) for calculating orthogonal coefficients was followed. The multiple range test of Duncan (*7*) was used to test the significance of the treatment means after variance analysis was applied.

RESULTS AND DISCUSSION

Growth Rate of the Tree-Trunk Circumference

There was a twofold increase in growth rate of the trunk circumference between those trees not supplied any P and those supplied with P at the lowest rate at the first measurement period of the early treatments (Table 3). The growth rate between trees not supplied any P and those supplied with P at the two highest rates increased threefold during this period. These differences in growth rates between trees of these treatments became smaller with each subsequent measurement period until, at the fourth and later measurement periods, no differences existed.

Trees supplied with P early grew faster than those supplied with P late in the first and second measurement periods. Trees supplied with P late grew faster than those supplied with P early only in the last measurement period, but the growth rate of all trees by this time was

Table 3. Effect of P fertilization on growth rate (mm/day) of tree-trunk circumference

Growth measurement period	P application	P, lb/acre 0	96	200	500	1001	Mean[z]
9/22/70–12/15/70	Early[x]	0.99 a	1.99 b	2.45 c	2.82 d	2.84 d	2.70
	Late	–[y]	–	2.28	2.37	2.57	2.40
	Mean[x]	[y]		2.36 a	2.59 b	2.71 b	**
12/15/70–3/9/71	Early	0.62 a	0.79 b	0.90 c	1.03 cd	1.12 d	1.02
	Late	–	–	0.87	0.90	1.00	0.92
	Mean			0.88 a	0.97 ab	1.06 b	*
3/9/71–6/1/71	Early	0.63 ab	0.57 a	0.58 a	0.60 ab	0.75 b	0.64
	Late	–	–	0.60	0.68	0.61	0.63
	Mean			0.59 a	0.64 a	0.68 a	ns
6/1/71–8/24/71	Early	0.19 a	0.14 a	0.14 a	0.12 a	0.13 a	0.13
	Late	–	–	0.10	0.11	0.14	0.11
	Mean			0.12 a	0.12 a	0.13 a	ns
8/24/71–11/16/71	Early	0.14 a	0.17 a	0.12 a	0.10 a	0.18 a	0.13
	Late	–	–	0.14	0.11	0.11	0.12
	Mean			0.13 a	0.11 a	0.14 a	ns
11/16/71–2/8/72	Early	0.14 a	0.19 a	0.22 ab	0.22 ab	0.31 b	0.25
	Late	–	–	0.19	0.25	0.29	0.24
	Mean			0.21 a	0.24 a	0.30 a	ns
2/8/72–5/2/72	Early	0.06 a	0.07 a	0.08 a	0.07 a	0.08 a	0.08
	Late	–	–	0.03	0.03	0.07	0.04
	Mean			0.05 a	0.05 a	0.07 a	ns
5/2/72–7/25/72	Early	0.08 a	0.03 a	0.04 a	0.03 a	0.06 a	0.04
	Late	–	–	0.11	0.07	0.08	0.08
	Mean			0.08 a	0.05 a	0.07 a	*

[x]Means in a horizontal column with different letters are significant at the 5% level (Duncan's multiple range test).

[y]– = no treatment was given; blank space = statistical analysis was not performed.

[z]Significance of means in a vertical column (F test): ** = 1% level, * = 5% level, ns = not significant.

relatively small and this difference is probably of littl: or no practical significance. The result obtained in this study is in agreement with that of Brenchley (*6*), who reported that the growth response of barley plants to P was greater in the early stages of growth.

Table 4 presents the variance analysis of the tree circumference growth rate at the first and second measurement periods. The analysis of growth rate for later measurement periods is not presented because differences were not statistically significant. The growth response to the P application rate was essentially linear. There was no significant rate X application interaction.

Fresh Weight of Petioles

In general, petioles of trees supplied with more P fertilizer were heavier than those supplied with less (Table 5). The differences in petiole weights among treatments were greater when trees were young than when old, which is in agreement with results obtained with the growth of the tree trunk (Table 3). In general, petioles from trees supplied with P early weighed more than those supplied late, particularly those petioles from trees that were relatively young. The petiole weight data were similar to the tree circumference growth rate data, in that early application of P was better than late for growth of papaya plants.

Fruit Yield

The fruiting response of the trees to P fertilization was substantial (Figure 1), a significant feature being the tremendous increase in

Table 4. Variance analysis of the growth rate of tree-trunk circumference

Source	Degree of freedom (df)	9/22/70–12/15/70 Mean square[x]	12/15/70–3/9/71 Mean square[x]
Block	5	0.1283	0.0444
Rate:			
Linear	1	0.6684**	0.1746**
Quadratic	1	0.0784	0.0023
Application	1	0.7951**	0.0812*
Rate X application	2	0.0589	0.00915
Error	25	0.0758	0.0153

[x]Significance (F test): ** = 1% level, * = 5% level.

Table 5. Effect of P fertilization on fresh weight (g/petiole) of petioles

Sampling date	Application	P, lb/acre 0	96	200	500	1001	Mean[z]
12/16/70	Early[x]	79.9 a	120.4 b	149.9 c	175.4 d	190.6 d	172.0
	Late	–[y]	–	143.6	154.3	162.9	153.6
	Mean[x]	y		146.8 a	164.8 b	176.8 c	**
4/14/71	Early	91.2 a	131.1 b	152.8 bc	154.7 bc	167.8 c	158.4
	Late	–	–	145.7	143.6	150.1	146.5
	Mean			149.2 a	149.2 a	159.0 a	ns
6/2/71	Early	92.9 a	126.0 b	145.1 c	158.4 c	175.5 d	159.7
	Late	–	–	141.1	151.4	156.0	149.5
	Mean			143.1 a	154.9 ab	165.8 b	ns
11/17/71	Early	115.9 a	150.7 b	175.6 c	186.0 cd	198.4 d	186.6
	Late	–	–	165.7	179.9	177.2	174.3
	Mean			170.6 a	182.9 ab	187.8 b	*
2/9/72	Early	69.9 a	76.1 b	88.5 c	86.5 bc	95.7 c	90.2
	Late	–	–	81.5	97.2	91.1	89.9
	Mean			85.0 a	91.9 a	93.4 a	ns
5/3/72	Early	64.8 a	71.2 a	85.0 b	86.3 b	101.1 c	90.8
	Late	–	–	77.9	97.4	96.0	90.4
	Mean			81.4 a	91.9 b	98.5 b	ns

[x]Means in a horizontal column with different letters are significant at the 5% level (Duncan's multiple range test).
[y]– = no treatment was given; blank space = statistical analysis was not performed.
[z]Significance of means in a vertical column (F test): ** = 1% level, * = 5% level, ns = not significant.

fruit-set in trees supplied with high amounts of P, particularly when applied at the early stage of growth. There was an increase of 155 percent in yield of marketable fruits (grades No. 1 and No. 2) between trees supplied with no P and those supplied with 96 lb. P/acre (Table 6). Trees supplied 1001 lb. P had a yield increase of 230 percent over trees not supplied any P. The difference in yield between these treatments decreased as the trees became older.

The total yield of fruits during the first 6 months of harvest was greater from trees supplied with P early than from trees supplied with P

Figure 1. Fruiting response to P fertilizer applied at the early stage of growth. Trees were 13 months old. Left, no P; middle, 96 lb. P/acre; right, 1001 lb. P/acre.

Table 6. Effect of P fertilization on fruit yield (lb/tree)

Harvest period and fruit grades	Time of P application	P, lb/acre					
		0	96	200	500	1001	Mean[z]
2/23/71–8/18/71 All grades	Early[x]	33.8 a	87.1 b	109.3 c	119.8 cd	125.8 d	118.3
	Late	–[y]	–	104.7	105.0	116.0	108.6
	Mean[x]	y		107.0 a	112.4 ab	120.9 b	*
2/23/71–8/18/71 Grades No. 1, No. 2	Early	27.8 a	71.0 b	83.7 c	87.0 cd	91.8 d	87.5
	Late	–	–	83.4	84.0	88.5	85.3
	Mean			83.6 a	85.5 a	90.2 a	ns
8/25/71–2/22/72 All grades	Early	52.4 a	80.0 b	96.5 c	104.3 c	121.9 d	107.6
	Late	–	–	93.0	101.5	108.6	101.0
	Mean			94.7 a	102.9 a	115.2 b	ns
8/25/71–2/22/72 Grades No. 1, No. 2	Early	50.2 a	72.8 b	84.2 c	87.4 cd	96.8 d	89.4
	Late	–	–	79.0	86.3	91.0	85.4
	Mean			81.6 a	86.8 ab	93.9 b	ns
2/29/72–7/25/72 All grades	Early	46.4 a	78.0 b	94.5 c	98.0 c	114.6 d	102.4
	Late	–	–	91.7	102.9	110.1	101.5
	Mean			93.1 a	100.4 b	112.3 c	ns
2/29/72–7/25/72 Grades No. 1, No. 2	Early	42.9 a	73.9 b	88.5 c	91.2 c	108.2 d	96.0
	Late	–	–	87.0	96.4	101.9	95.1
	Mean			87.7 a	93.8 b	105.0 c	ns
2/29/72–7/25/72 Grade No. 1	Early	40.3 a	62.0 b	81.8 c	84.3 c	98.2 d	88.1
	Late	–	–	79.4	88.6	93.2	87.1
	Mean			80.6 a	86.4 a	95.7 b	ns

[x]Means in a horizontal column with different letters are significant at the 5% level (Duncan's multiple range test).
[y]– = no treatment was given; blank space = statistical analysis was not performed.
[z]Significance of means in a vertical column (F test): * = 5% level, ns = not significant.

late. During this period, however, when the marketable fruits (grades No. 1 and No. 2) of these two treatments were compared, there was a small difference in yield, which was not statistically significant. Trees receiving the early P applications had greater fruit yield than those receiving the late P, probably because of the greater number of fruits produced in the former, although the fruit was smaller. Our result on papaya yield is in agreement with that of Jones and Warren (*10*), who reported that in tomato plants a greater yield resulted when P was applied at planting time than when it was applied to established plants.

During the second 6 months of harvest, the difference in yield between trees supplied with P early and late persisted, but this difference was not statistically significant. The last 5 months of harvest revealed no difference either in total yield or in graded fruits between trees supplied with P early and late. It should be mentioned here that even in late treatment trees there was an increase in yield when trees were given more P, but these differences were not as great as those of the early treatments.

In trees not supplied with any P, the rate of plant development and, hence, the time of first fruit harvest were delayed about 6 weeks longer than trees supplied with P. This is in agreement with Glover's report (*8*) that deficiencies of N and P—particularly the latter—in maize delayed the stages of tasseling and silking. The result in this study also agrees with Specht's observation (*18*) that when heath vegetation growing on P-deficient sandy soil in South Australia was supplied with P, it flowered 2 years earlier than the control. It appears that in papaya, and some other fast-growing plants, P is needed particularly for vegetative growth early in the growth cycle so that later development is not delayed.

Percentages of Indicated Grades of Fruits Harvested

The percentages of marketable fruits (grades No. 1 and No. 2) decreased while those of the culls increased as the trees were supplied with more P fertilizer, particularly at the early stage (Table 7). This result was particularly noticeable at the first fruit harvest period but was also observed at the second period. As the trees aged, the treatments did not affect the size of the fruits very much. One treatment that appears promising for production of a high percentage of marketable fruits and low percentage of culls is that in which trees were given 96 lb. P/acre early.

Table 7. Percentages of indicated grades of fruits harvested from trees in the treatment plots

Date of harvest	Grade of fruit	P, lb/acre							
		Early					Late		
		0	96	200	500	1001	200	500	1001
2/23/71–8/18/71	No. 1 and No. 2	82.3	81.4	76.5	72.6	72.9	79.7	80.0	76.3
	Culls	17.7	18.6	23.5	27.4	27.1	20.3	20.0	23.7
8/25/71–2/22/72	No. 1 and No. 2	95.8	90.9	87.2	83.8	79.4	84.9	85.0	83.8
	Culls	4.2	9.1	12.8	16.2	20.6	15.1	15.0	15.2
11/24/71–2/22/72	No. 1	94.0	93.1	90.9	85.9	80.9	90.0	90.2	89.4
	No. 2	4.2	4.4	6.1	8.3	13.5	6.7	6.2	7.7
	Culls	1.8	2.5	3.0	5.8	5.6	3.3	3.6	2.9
2/29/72–7/25/72	No. 1	87.0	87.2	86.6	85.9	85.7	86.6	86.2	84.7
	No. 2	5.4	7.6	7.5	7.2	9.0	8.3	7.7	8.2
	Culls	7.6	5.2	5.9	6.9	5.3	5.1	6.1	7.1

Relations Between P Fertilization and *A*, Yield of Marketable Fruits, and *B*, Percentage of Marketable Fruits

During the first harvest period (from February 23, 1971 to August 18, 1971), yield of marketable fruits (grades No. 1 and No. 2) was higher from trees in the early than in the late treatment, but the percentage of marketable fruits in the former treatment was significantly lower than in the latter (Figure 2). This indicates that if P fertilizer is applied at 200 lb/acre or more prior to the flowering of papaya plants, the percentage of marketable fruits will be lowered significantly. In the late treatment, yield from trees supplied with P at 200 lb/acre was not significantly lower than from trees supplied at 500 lb/acre or more, indicating that P at 200 lb/acre was adequate for optimal yield during this period.

During the second harvest period (from August 25, 1971 to February 22, 1972), yield of marketable fruits remained higher in the early than in the late treatment (Figure 3). The percentage of marketable fruits was still higher in the latter than in the former treatment, although this difference was not as great as that of the earlier harvest period (Figure 2). Yield from trees supplied with P at 200 lb/acre was 8.4 percent lower than from trees supplied with P at 500 lb/acre in the late treatment, but this difference was not statistically significant.

During the third harvest period (from February 29, 1972 to July 25, 1972), there was no difference either in yield or in percentage of marketable fruits between trees of the early and late treatments (Figure 4). Yield from trees supplied with P at 200 lb/acre was 9.8 percent lower than from trees supplied with P at 500 lb/acre in the late treatments, indicating that whereas P at 200 lb/acre was adequate during the first harvest period, it was not adequate during the last 5 months of harvest. This may be due to the fact that P was not applied to trees in the late treatments after December 29, 1971, and, therefore, trees supplied with P at 200 lb/acre, particularly, were in need of this nutrient during the last harvest period.

Average Weight of Harvested Fruits

The harvested fruits from trees supplied with P early weighed less on an average than those from trees supplied late during the first year of harvest (Table 8). The most promising treatment for maximum weight appears to be 96 lb. P/acre; this treatment was also commended when the proportionate sizes of harvested fruits were considered (Table 7).

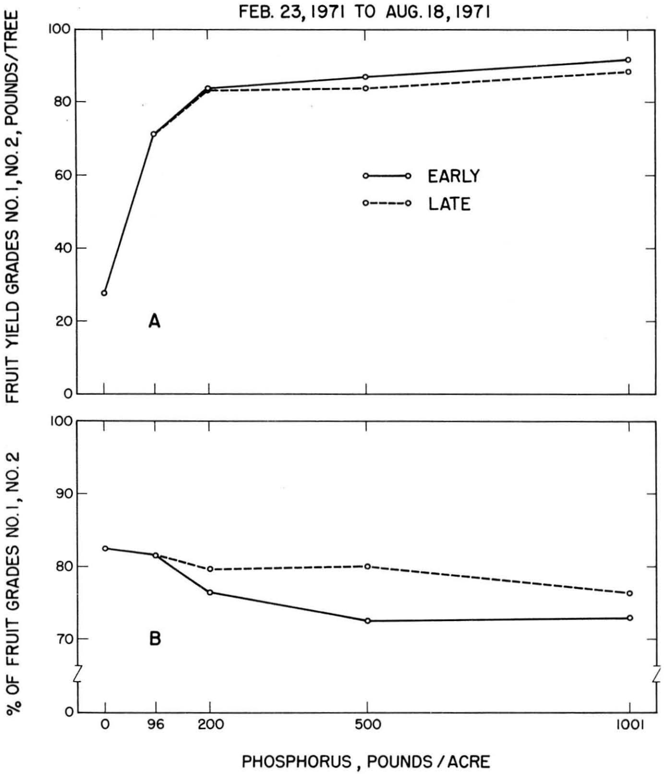

Figure 2. Relations between P fertilizer amounts and *A*, yield of fruit grades No. 1 and No. 2, and *B*, percentage of fruit grades No. 1 and No. 2 during the first fruit harvest period.

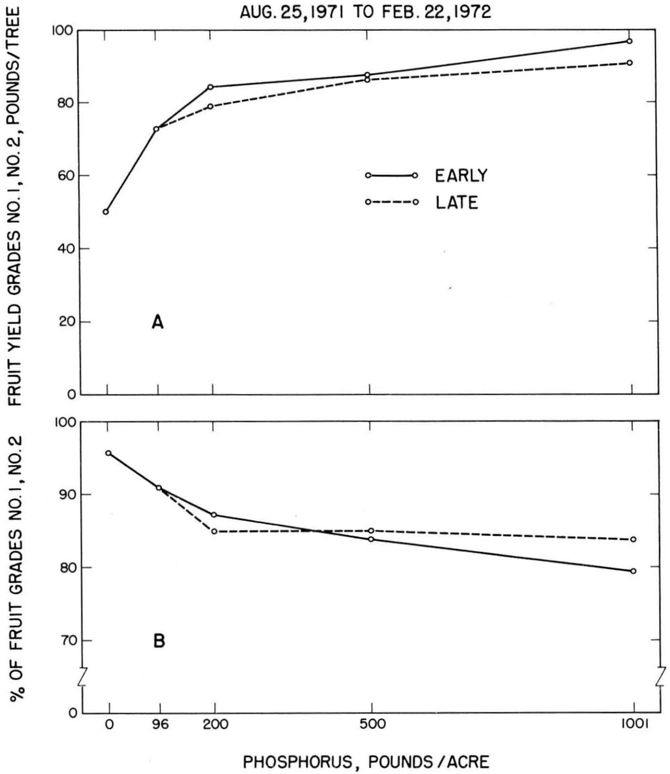

Figure 3. Relations between P fertilizer amounts and *A*, yield of fruit grades No. 1 and No. 2, and *B*, percentage of fruit grades No. 1 and No. 2 during the second fruit harvest period.

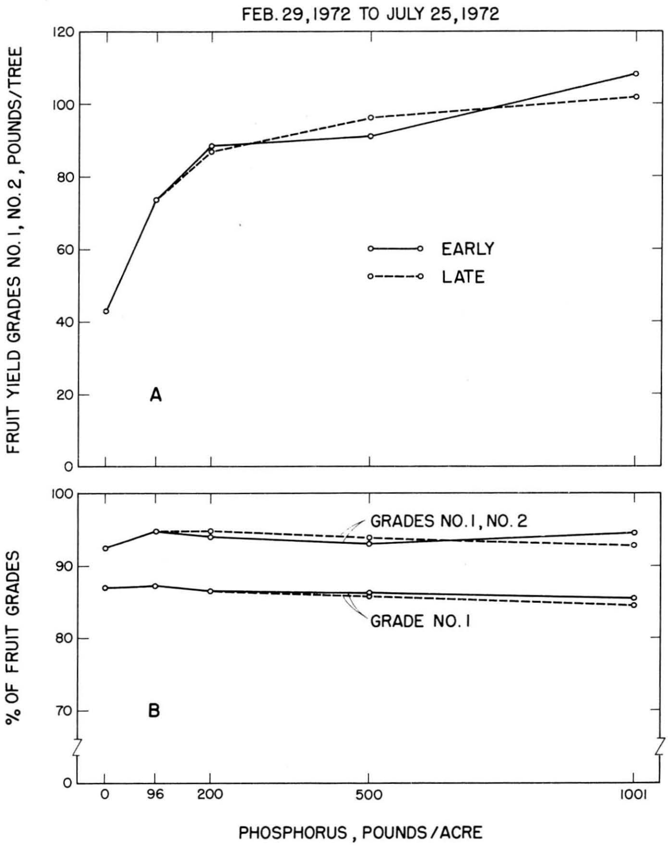

Figure 4. Relations between P fertilizer amounts and *A*, yield of fruit grades No. 1 and No. 2, and *B*, percentage of fruit grades No. 1 and No. 2 during the third fruit harvest period.

Table 8 also shows that, during the first year, fruits harvested from trees supplied a low (96 lb. P/acre) amount of P were heavier on the average than those not supplied with any P, although this difference was not statistically significant. It may be that a greater amount of water was absorbed by these fruits than by the fruits of trees not given any P.

Fruit Total Soluble Solids Contents

In general, the concentration of the fruit soluble solids was not affected much by the P treatments (Table 9); however, there was a

Table 8. Effect of P fertilization on average weight (lb/fruit) of harvested fruits

Harvest date	P application	P, lb/acre 0	96	200	500	1001	Mean[z]
2/23/71–8/18/71	Early[x]	1.029 ab	1.074 a	1.004 ab	0.959 b	0.988 b	0.984
	Late	–[y]	–	1.027	1.045	1.021	1.031
	Mean[x]	y		1.015 a	1.002 a	1.004 a	*
8/25/71–2/22/72	Early	1.042 ab	1.095 a	1.007 b	0.963 b	0.962 b	0.977
	Late	–	–	1.028	1.036	1.023	1.029
	Mean			1.018 a	1.000 a	0.992 a	*
2/29/72–7/25/72	Early	1.017 a	1.061 a	1.036 a	1.063 a	1.076 a	1.058 a
	Late	–	–	1.059	1.104	1.090	1.084 a
	Mean			1.047 a	1.083 a	1.083 a	ns

[x]Means in a horizontal column with different letters are significant at the 5% level (Duncan's multiple range test).
[y]– = no treatment was given; blank space = statistical analysis was not performed.
[z]Significance of means in a vertical column (F test): * = 5% level, ns = not significant.

Table 9. Effect of P fertilization on fruit soluble solids (% of fresh matter)

Sampling date	P application	P, lb/acre					
		0	96	200	500	1001	Mean[z]
6/2/71	Early[x]	14.2 a	13.6 b	13.4 b	13.2 b	13.6 b	13.4
	Late	–[y]	–	13.3	13.5	13.5	13.4
	Mean[x]	[y]		13.4 a	13.4 a	13.6 a	ns
9/29/71	Early	14.7 a	14.3 a	14.3 a	14.2 a	14.0 a	14.2
	Late	–	–	14.3	14.2	14.3	14.2
	Mean			14.3 a	14.2 a	14.2 a	ns
4/15/72	Early	13.8 a	14.1 a	14.2 a	14.1 a	14.0 a	14.1
	Late	–	–	13.9	13.8	13.7	13.8
	Mean			14.0 a	14.0 a	13.8 a	*

[x]Means in a horizontal column with different letters are significant at the 5% level (Duncan's multiple range test).
[y]– = no treatment was given; blank space = statistical analysis was not performed.
[z]Significance of means in a vertical column (F test): * = 5% level, ns = not significant.

trend indicating that P fertilization lowered the soluble solids content, particularly when high amounts of P were used.

Petiole-P Concentrations

There were significant differences in petiole-P concentrations among trees supplied P early, particularly in petioles sampled when trees were young (Table 10). These differences persisted throughout the study but became much smaller as the trees grew older. In trees supplied with the highest amount of P early, the petiole-P concentration was highest at the first sampling date, declined substantially in the June 2 samples, and remained at about this concentration in later samples. Petiole P of trees not supplied with any P was extremely low at the first sampling date but gradually became higher in petioles sampled later, peaking about 1 year after the start of the treatments.

Petiole P was higher in trees given P fertilizer early than in those given P late in the December 16 and April 14 samples only. There was no difference in petioles sampled on June 2 and November 17. In trees supplied with P late, petiole P was higher than in trees supplied with P early, at the last sampling date.

Table 10. Effect of P fertilization on concentration of petiole P (% of dry matter)

Sampling date	P application	P, lb/acre 0	96	200	500	1001	Mean[z]
12/16/70	Early[x]	0.104 a	0.159 b	0.190 c	0.230 d	0.280 e	0.233
	Late	–[y]	–	0.179	0.195	0.222	0.199
	Mean[x]	y		0.185 a	0.212 b	0.251 c	**
4/14/71	Early	0.104 a	0.150 b	0.194 c	0.228 d	0.263 e	0.229
	Late	–	–	0.193	0.198	0.246	0.213
	Mean			0.194 a	0.213 b	0.255 c	*
6/2/71	Early	0.120 a	0.157 b	0.177 bc	0.193 cd	0.210 d	0.194
	Late	–	–	0.184	0.188	0.209	0.194
	Mean			0.180 a	0.191 a	0.210 b	ns
11/17/71	Early	0.128 a	0.159 b	0.191 c	0.211 d	0.228 e	0.210
	Late	–	–	0.190	0.200	0.223	0.204
	Mean			0.190 a	0.206 b	0.226 c	ns
2/9/72	Early	0.114 a	0.139 b	0.162 c	0.175 c	0.194 d	0.177
	Late	–	–	0.155	0.186	0.206	0.182
	Mean			0.158 a	0.180 b	0.200 c	ns
5/3/72	Early	0.126 a	0.140 a	0.162 b	0.200 c	0.226 d	0.196
	Late	–	–	0.185	0.204	0.249	0.213
	Mean			0.174 a	0.202 b	0.238 c	*

[x]Means in a horizontal column with different letters are significant at the 5% level (Duncan's multiple range test).
[y]– = no treatment was given; blank space = statistical analysis was not performed.
[z]Significance of means in a vertical column (F test): ** = 1% level, * = 5% level, ns = not significant.

Table 11. Effect of P fertilization on water content and petiole nutrient composition

Sampling date and treatment	Petiole moisture (percent)[x]	Dry weight of petiole[y]								
		Percent				ppm				
		N	K	Ca	Mg	Fe	Mn	Zn	Cu	B
12/16/70										
1	88.57 a	1.41 abc	3.35 a	1.06 b	0.33 a	24 a	22 a	12 b	5.0 a	24 a
2	89.22 b	1.31 a	3.54 a	0.88 a	0.27 b	23 a	24 ab	14 a	4.9 a	24 a
3	89.22 b	1.45 bc	3.58 a	0.86 a	0.27 b	21 a	25 ab	13 ab	4.5 b	24 a
4	89.58 c	1.54 c	3.48 a	0.91 a	0.26 b	18 a	22 a	12 b	3.5 b	25 a
5	89.97 d	1.51 c	3.46 a	1.11 b	0.24 b	19 a	27 b	10 c	3.5 b	24 a
4/14/71										
1	88.83 a	1.32 ab	3.49 a	0.99 a	0.34 a	23 a	29 a	14 a	4.9 a	22 a
2	89.70 a	1.27 a	3.64 a	1.01 ab	0.27 b	22 a	28 a	14 a	4.6 a	22 a
3	89.47 a	1.37 bc	3.89 a	1.04 ab	0.25 b	29 a	27 a	14 a	3.7 b	21 a
4	89.37 a	1.45 c	3.90 a	1.09 bc	0.24 b	19 a	26 a	14 a	3.7 b	22 a
5	89.62 a	1.44 c	3.84 a	1.15 c	0.21 c	25 a	28 a	14 a	4.0 b	22 a
6/2/71										
1	88.70 a	1.13 a	3.36 a	1.09 bc	0.31 a	20 a	21 a	11 a	4.5 a	24 a
2	89.12 b	1.16 a	3.53 a	1.05 b	0.28 b	20 a	22 a	12 a	4.0 b	25 a
3	89.27 bc	1.18 a	3.66 a	0.97 a	0.24 bc	18 b	21 a	11 a	3.6 c	24 a
4	89.37 bc	1.20 a	3.48 a	1.08 bc	0.25 b	18 b	23 a	11 a	3.5 c	25 a
5	89.28 c	1.19 a	3.56 a	1.14 c	0.21 c	18 b	23 a	11 a	3.4 c	24 a

[x]Fresh weight basis.
[y]Means in a vertical column with different letters are significant at the 5% level (Duncan's multiple range test).

Water and Mineral Composition of the Petiole

The water and mineral composition of the petioles sampled at the flowering and early fruit-bearing stages of plants in the early treatments are presented in Table 11. Analytical data for samples of November 17, 1971, February 9, 1972, and May 3, 1972 are not presented because the influence of P on the composition of the other nutrients was not as great as in the samples taken earlier. The concentrations of N and K were generally adequate throughout this study (*2,3*).

To express the relations between petiole P and the other nutrients quantitatively, correlation coefficients were determined (Table 12). Petiole moisture was more highly correlated positively with petiole P than with any other component. Petiole N and petiole K were also significantly correlated positively with petiole P. Our result of petiole P with petiole water, N, and K, with the exception of calcium (Ca), is in agreement with that of Rege and Sannabhadti (*14*), who reported that in India P fertilization increased the water content and accelerated the uptake of N, K, and Ca into the leaves of sugarcane. Our result on N is also in agreement with that of Ulrich (*19*), who reported that P fertilization increased the concentration of nitrate N in petioles of the sugar beet. The relations of P to petiole water, N, and K in this present study, however, are in contrast with those reported by us previously (*2*) on the influence of petiole N on petiole water and K. In that study, higher petiole-N concentrations were invariably associated with lower petiole concentrations of water, K, and P.

Petiole concentrations of magnesium (Mg) and those of Cu were negatively correlated with petiole-P concentrations (Table 12). Our result on the relation of P with Mg indicates the possibility that in some cases excessive P fertilization of papaya may result in Mg deficiency where the soil supply of the latter is borderline. Our result of P with Cu agrees with those reported for oranges in Florida (*15*) and California (*5, 11*) and for avocado in California (*12*). Our result, however, was not as drastic as that of Bingham and Martin (*5*), who reported that leaf Cu in citrus decreased from 7 to 2 parts per million (ppm) as a result of high P fertilization.

The concentrations of Ca, Fe, Zn, Mn, and B were not affected significantly by P fertilization.

Variables Affecting Petiole P

The amount of P fertilizer applied and the square of this variable accounted for 90.6 percent of the variance of the petiole-P concentra-

Table 12. Correlation coefficients between petiole-P concentrations and water and the other nutrients

Sampling date	Petiole moisture[x]	N	K	Ca	Mg	Fe
12/16/70	0.843**	0.527**	0.192	0.155	−0.704**	−0.357
4/14/71	0.366*	0.380*	0.531**	0.343	−0.882**	0.042
6/2/71	0.745**	0.480**	0.429*	0.062	−0.641**	−0.381*

Sampling date	Petiole moisture[x]	Mn	Zn	Cu	B
12/16/70	0.843**	0.299	−0.534**	−0.482**	0.181
4/14/71	0.366*	−0.284	−0.107	−0.519**	−0.028
6/2/71	0.745**	0.213	0.143	−0.433*	0.228

[x]Significance: *= 5% level, ** = 1% level.

Table 13. Effect of the indicated variables on the concentrations of petiole P

Independent variable[x]	R^2	F of the indicated variable[y]			Standard partial regression coefficient		
		P	P^2	H	P	P^2	H
P, P^2	.906	72.8**	22.5**				
P, P^2, H	.923			6.0*	+1.598	−0.890	+0.223

$$\hat{Y} = -2.121 + 0.149P - 0.042P^2 + 0.025H$$

[x]Symbols: P = lb. P/tree; H = % petiole water, 12/16/70.
[y]Significance (F test): * = 5% level, ** = 1% level.

tions on December 16, 1970 (Table 13). The concentration of petiole moisture was another significant variable.

The P Critical Level

Because yield of marketable fruits from trees supplied with P late at 200 lb/acre was at the breaking point of the yield response curve, and the percentage of marketable fruits was relatively high (Figures 2, 3, 4), petiole-P concentrations from this plot seem suitable to serve as the P critical level. The mean (0.186 percent), derived from petiole concentrations at all sampling dates except the one from February 9, 1972, was designated as the P critical level of papaya; for a practical reason, the mean was set at 0.185 percent.

Fertilizer Recommendations

For papaya plants grown on virgin a'a lava soil in the Puna area on the Island of Hawaii, the P treatment at 202 lb/acre (102 lb. during the vegetative stage and 100 lb. from flowering through bearing, with modifications discussed below) appears appropriate. Because there is a possibility that the percentage of marketable fruits can be raised further by applying less P at the vegetative stage than the amount used in this study, and because there was evidence that the trees needed more P to maintain yield toward the end of the fruit harvest, P at 17 lb/acre was subtracted from the 102 lb. scheduled for application before flowering, and this amount (17 lb.) was added to the 100 lb/acre for application during the last 5 months of fruit harvest. Hence, the following fertilization is recommended: P at 85 lb/acre from the vegetative to the bearing stage and at 9.7 lb/acre at 6-week intervals during the bearing stage. A suggested P fertilization schedule during the vegetative stage is presented in Table 14. Petioles from trees under this P fertilization schedule should be sampled at stages of flowering and bearing to ascertain that petiole P of these trees is at the P critical level.

When trees are planted in an area where papaya has been grown before, considerably less P than 85 lb/acre should be applied to plants during the vegetative stage. At flowering, petioles should be sampled to ascertain the petiole-P concentration, and if the latter is below the critical level, P fertilizer should be applied according to information derived from Figure 5. If petiole P is 0.16 percent at flowering, 18 lb. P/acre at 6-week intervals should be applied five times (92 lb. P/acre total) to the plants so that petiole P of plants at the bearing stage would be raised to 0.185 percent. If petiole P is 0.14 percent, 20 lb. P/acre at 6-week intervals should be applied six times (120 lb. P/acre total) to the plants so that petiole P would be raised to 0.185 percent. Petioles should be sampled at the bearing stage to check on the P application rates recommended.

The critical P level determined in the present study applies to the P nutritional status of plants at the flowering and bearing stages in the Puna area, but it may also apply to that of papaya plants grown in other areas of the State of Hawaii. The N critical level, determined at the Waimanalo Research Station, Island of Oahu, under different soil and climatic conditions from those at Puna, was found to be essentially the same as that determined at the latter (*4*), and it is therefore probably applicable to papaya plants grown in other areas of the State of Hawaii. Since this was so for the N level, the P critical level

Table 14. A suggested P fertilization schedule for papaya plants grown on virgin a'a lava soil at Puna, from the time seeds are sowed to the time plants are budding

Age of plant (months)	Developmental stage of plant	P, lb/acre
0	Seed	3
1.5	Vegetative	3
2.5	Vegetative	3
3.5	Vegetative	6
4.0	Vegetative	12
5.0	Vegetative	24
6.0	Bud	34
Total P, lb/acre		85

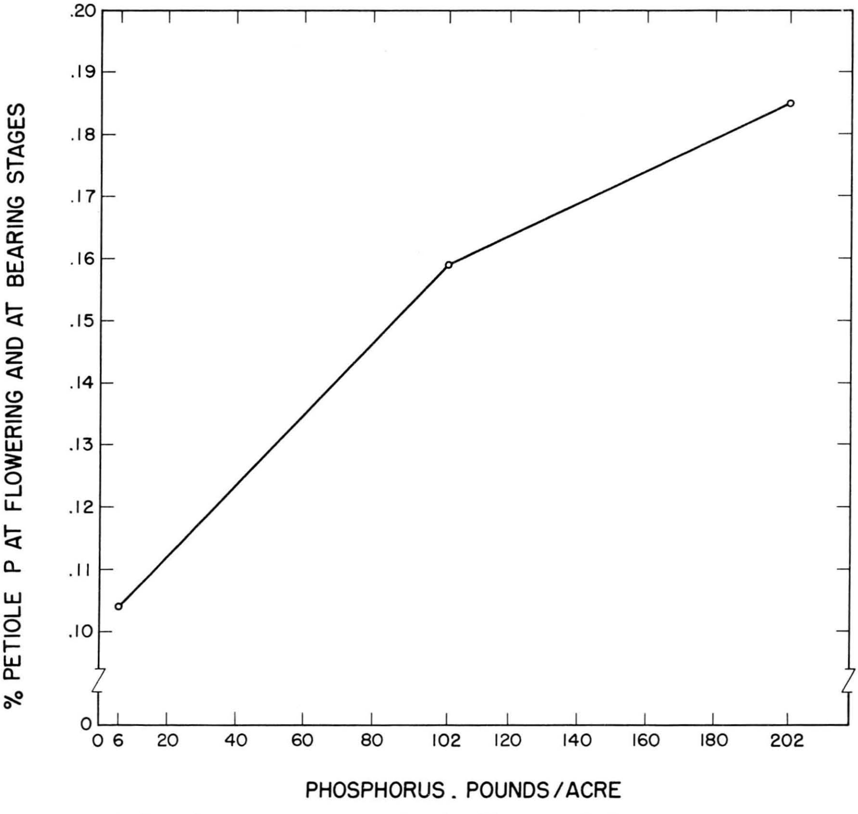

Figure 5. Relations between amount of P fertilizer applied late and concentration of petiole P.

determined at Puna may also apply to papaya plants grown in other areas of the State of Hawaii.

SUMMARY

The critical petiole-P level for optimal fruit yield of papaya was determined on trees grown on a'a lava soil at Puna, Island of Hawaii. Tremendous growth and fruit yield responses to P fertilization were obtained, although the proportion of smaller-sized harvested fruits became greater as trees were supplied with more P. The concentration of soluble solids of fruits from trees under heavy P fertilization was also lowered. In the determination of critical P level, therefore, the factors mentioned in this bulletin were considered along with the marketable yield of fruits.

The concentrations of petiole water, N, and K increased with P fertilization, while those of Mg and Cu decreased.

The rates of P application and the concentration of petiole moisture were the only two significant variables that affected the concentrations of petiole P.

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Hawaii Agricultural Experiment Station
College of Tropical Agriculture, University of Hawaii
William R. Furtick, Dean of the College and Director of the Experiment Station
Noel P. Kefford, Acting Associate Director of the Experiment Station
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